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Engineering Design Integration & Non-Destructive Testing for the ESS accelerator

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Abstract The ESS linac is under construction by the ESS partner institutes (so-called In-Kind Contributors - IKC) and will operate the most powerful proton beam ever for neutron spallation source. The linac delivers 5 MW via 2 GeV protons at a repetition rate of 14 Hz at the He-cooled solid tungsten target. The pulsed neutrons, result of the spallation, will reach the science instruments after having been moderated. The engineering effort needed to assemble the linac and its RF sources (klystrons), commenced with the design integration and currently is undergoing installation planning. In addition, the first dedicated engineering properties experiments, so-called Non-Destructive Testing for Accelerators (NDTA), take place to map and pilot the innovative testing strategy for the ESS linac structural materials. The Engineering Resources Group (ERG) of the Accelerator Division (AD) has been created to provide services of design integration, mechanical engineering and system engineering to ESS Accelerator Systems (ACCSYS) that are applicable across work package boundaries and principles of the linac systems. In parallel, part of the machine integration is the physical plant coordination and supervision. At last, in order to fulfill the missions of feasibility and planning, the ERG designs and leads the development of the technical laboratories for the accelerator systems. The current citation describes the engineering proposal for the mechanical design study and integration of the linac machine, its non-destructive testing and the essential development of the technical areas to service the long-term operational needs.

Keywords European Spallation Source, ESS, engineering design integration, Non-Destructive Testing for Accelerators, NDTA

INTRODUCTION

The European Spallation Source (ESS), the new generation facility of neutron spallation sources is under construction and installation in Lund (Sweden) since June 2014. The 5 MW proton beam of the ESS accelerator, with a peak power of 125 MW, will be able to deliver 2 GeV beams with a peak beam current of 62.5 mA on the helium cooled ESS tungsten target. The linac beam will have a repetition rate of 14 Hz with a long pulse length of 2.86 ms that correspond to a 4% duty factor. The pulsed neutrons at high fluxes, result of the tungsten spallation, will then undergo energy regulation in the moderators and will reach the instruments which house a wide variety of detectors and experimental stands.

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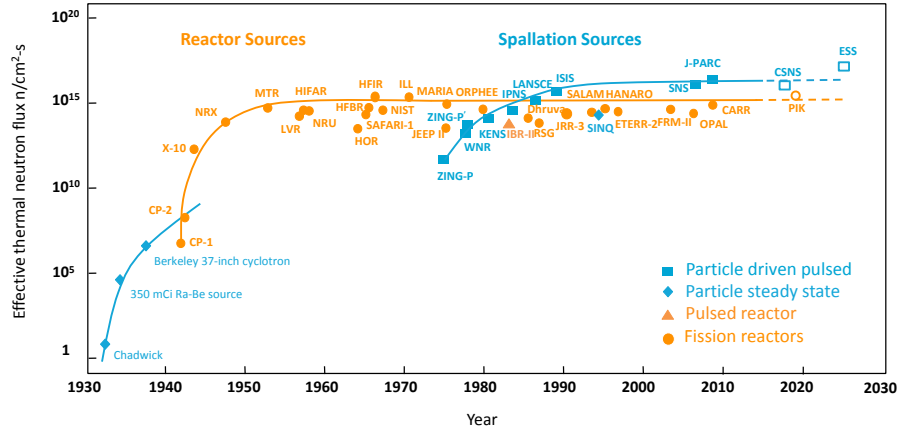


Fig. 1. Neutron sources over the last 100 years, updated from Neutron Scattering, K. Skold and D. L. Price, eds, Academic Press, 1986 [1]

The approximately 600 m long linac requires RF power generated by over 150 individual high power RF sources, at an approximate cost of over 200 M€. The ESS partner institutes all over Europe realize the ESS machine by covering its cost: either by contributing to the budget or via the so-called In-Kind Contributions (IKC) in machine parts. The engineering design integration and modelling of the entire ESS facility is achieved by the digital 3D representation called ESS Plant Layout (EPL), containing civil infrastructure, machines and auxiliary systems. Through the online platform Collaboration Home for ESS (CHESS) [2], the up-to-date model and date information is available online worldwide.

ENGINEERING APPROACH OF THE ESS ACCELERATOR

The ESS accelerator consists of a warm linac (room temperature) and a following cold linac (cryogenic at 2K temperature). The major sections of the ESS accelerator are presented in Fig. 2.

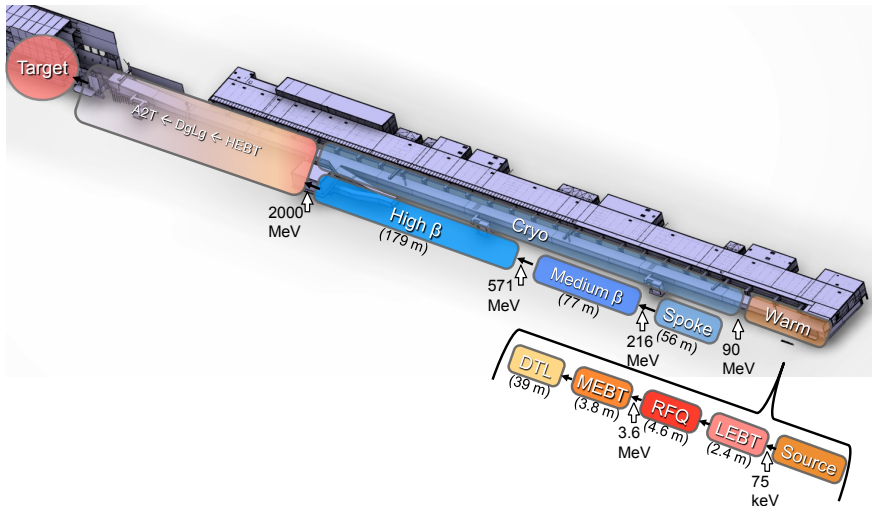


Fig. 2. Schematic layout of the ESS accelerator

During the early engineering design, the machine construction and later the engineering integration phase of the ESS accelerator, several strategic steps were identified and followed to match the technical challenges of the project:

1. The machine was firstly described in a set of technical specifications, the machine requirements. Structural, interface and technical requirements were generated to describe the linac.
2. The engineering design of the machine took place, including the structural material selection with dedicated and extended testing.
3. At this point, it is worth mentioning that the future commissioning planning as well as both potential optimization was taken into consideration. Although this is not an absolutely essential step, indeed it has been identified as critical for the beam time availability during the initial start-up but also steady-state operations.
4. Next step was the fabrication of the first prototypes and experimentation. In an alternative case when time could allow it, this is the step that includes the development, manufacturing and testing of the machine mock-ups.
5. Implementation of the Non-Destructive Testing (NDT) came right afterwards. It is of prime importance to introduce at this stage and potentially update the machine design so as to efficiently integrate the NDT devices accordingly. The NDT methodology has to be adapted to the accelerator or its sub-assemblies which are identified as critical for failure or long-term machine operations.
6. Having reached a mature understanding of the accelerator design, the series production initiated for the machine components. The ESS IKC proceeded to the manufacturing, control and verification, assembly and intermediate lab installation of the machine components that will later transport to Lund for final installation in the ESS tunnel.

ENGINEERING DESIGN INTEGRATION [4]

The ESS accelerator and the rest of the ESS machines (target, instruments) are integrated with the ESS physical plant in the EPL 3D-model. This facility master model is maintained in a dedicated CAD system. All machines are assembled on a relevant 3D-point skeleton, which is generated by the most up-to-date lattice information from beam physics. In order to achieve the precise and on-time implementation, the lattice is published in LinacLego [5], together with the machine technical specification.

The EPL also incorporates civil engineering and the rest of the 3D information that lack of CAD correlation with the lattice. Therefore, although a Facility Breakdown Structure (FBS) has been developed in ESS and is currently under optimization, a Location Breakdown Structure (LBS) is defined in parallel. Together, the FBS and LBS express the agreed requirements and combine all CAD and data information that describe the entire ESS facility. Both before mentioned structures are also integrated in the facility PLM¹, being part of a unified system that relates firmly CAD and other types of information (contracts, etc.) together with engineering data.

¹ PLM: Product Lifecycle Management

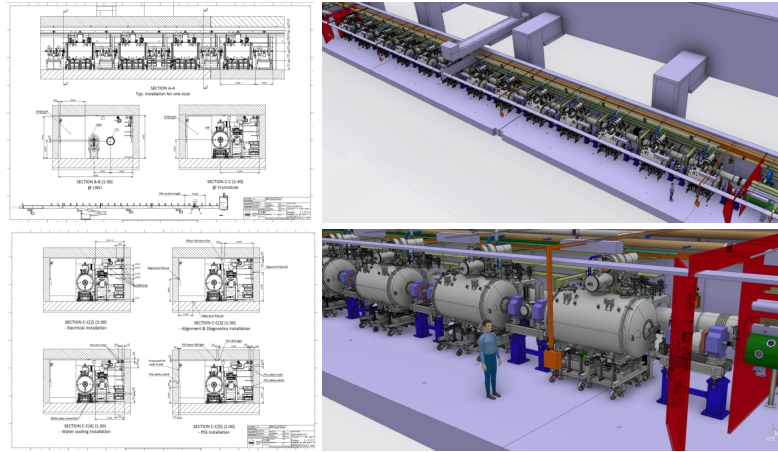


Fig. 3. Design of the spoke (SPK) tunnel section of the ESS accelerator
(ESS-0030574)

NON-DESTRUCTIVE TESTING FOR ACCELERATORS (NDTA)

The ESS accelerator project plan [7] demands efficient results in reliability and availability of neutron beams during operations. To successfully implement the efficient operation scheme dedicated studies have been made [8]. In this way, it will be possible for the future users to utilize for their needs the neutron beams according to the operations plan.

The accelerator is the primary dedicated tool of ESS put in action for the production of the neutrons. The accelerator operations plan includes as well specified goals on the reliability and availability of the accelerator machine itself. Consequently, preventive engineering and regular maintenance is needed on the accelerator so as to serve the nominal ESS operations scheme. Accelerator components are designed with precisely calculated factors of safety to ensure safe and reliable operation over their lifetime. Despite their design the knowledge of the actual current material state remains an issue under investigation, yet to be fully attained. In addition, non-destructive mechanical testing is investigated for its potential, as an asset to contribute to the reliability, availability and efficiency of this leading laboratory with cutting-edge technology and accelerator applications [9]. In this framework, the project of Non-Destructive Testing for Accelerators – NDTA was founded in ESS with the innovative conceptual orientation of application of the Resonant Ultrasound Spectroscopy (RUS) testing on accelerator systems.

For the methods and applications discussed, emphasis is placed on providing capabilities, which are predictive in nature, in identifying and sensing conditions that lead to detrimental material behavior instead of locating defects after they have developed. NDTA technologies are proposed for rapid assessment of broken down behavior for varying geometries and structural materials of the accelerator. Beam diagnostics and in parallel the traditional engineering monitoring methods are based on detection of beam instabilities or misbehavior and/or leaks, cracks, optical defects or other; without providing information about the source of destruction or the current status of the material. The use of a number of correlated transducer sensors is proposed to monitor real-time material properties. Such technologies enable advanced

predictive modeling and improved safety requirements for effective monitoring and material-state control capabilities

The RUS is widely used in both industrial fields and research labs for the non-destructive certification of components of various sizes, materials, etc. The application of RUS testing and Laser driven RUS (L-RUS) have also been introduced in high-tech fields for preventive maintenance and calibration plus monitoring of the relative engineering properties.

Various factors might affect the capability of waves to travel inside a medium and consequently affect its amplitude, frequency or other characteristics transmitted by the probe to the sensor system. However, the ultrasound waves utilized in this methodology can penetrate through a variety of different material layers and travel throughout the accelerator structural materials, revealing the changes and alterations of its areas at a distance via the produced spectra.

The leading benefit of implementing RUS on the accelerator field is the applicability of the NDTA and relevant measurements on both reference and radiation backgrounds. In order to service the challenging goals of beam availability and machine reliability for ESS, the following technical issues are set as objectives to be addressed by the NDTA with respect to each of the ESS machines:

1. Real-time diagnostics of the micro- and macro- properties of the accelerator slot² components and engineering behavior of the accelerator components
2. Monitoring of the integrity of the slot components
3. Schedule interventions (according to the ESS operations plan) for preventive maintenance
4. Reduce maintenance time and lower beam down-times
5. Gathering of information for the calibrated (normal) spectrum response of the ESS accelerator slots
6. Creation and maintenance of a database for capturing and maintaining the engineering (structural, modal, etc.) properties and information for the structural response of dedicated accelerator slots
 - a. during beam-off (reference background)
 - b. during beam-on (radiation background)
7. Measuring of the resonant response of the machine during shut-downs so as to check the slot integrity
8. Experimental modal definition of the ESS accelerator resonant response

Disruptions of the structural integrity of the accelerator systems or their auxiliary components are proportionally apparent through changes in the resonant modes, monitored by RUS. Deviations from the calibrated (normal) spectrum can be exhibited by one or more of the characteristics presented in Fig. 4 [9], [10].

² Slots are defined as installation sub-assemblies of the ESS accelerator [4]

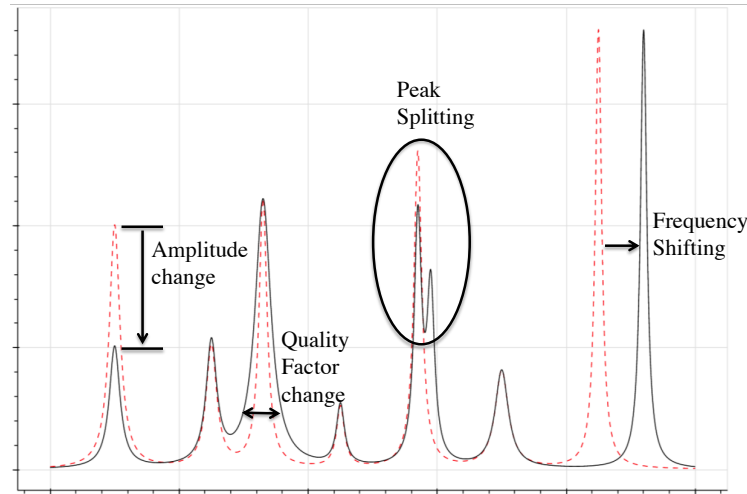


Fig. 4. Four possible changes in the resonant spectrum due to material deformation [9], [10]

1. The resonant mode is identified by the optical system, so in the degree that it gets disrupted, it results in changes to the observed amplitude.
2. A specified (or pre-selected) mode may be attenuated or reduced due to interactions with the accelerator operation or high radiation background or by the early formation of cracks.
3. New resonant frequencies may appear as the structural material of a component degenerates towards breaking down.
4. Dimensional changes (micro-level) may also shift the identified resonant frequency up or down, depending on the nature of the perturbation.

Also, one of the advantages of putting in use the NDTA is that the degree of deformation on the accelerator systems is immediately evident upon its creation. Deformations can be induced by miscellaneous factors such as loads, friction due to dynamic behavior of components, thermal dilatation or accelerator induced radiation background.

The following technical issues are controlled through RUS with respect to the ESS accelerator parts and other material samples:

1. Real-time diagnostics of the micro- and macro- properties of the machine components and monitoring of the engineering behavior of the components.
2. Identification of the status and structural integrity of the machine components.

SUMMARY

A promising NDTA methodology is designed accordant to the engineering integration for the ESS accelerator for the control of structural quality and operations of the machine sub-assemblies.

The first NDTA results and strategy are based on RUS, but gradually it is expected to be combined with Laser-RUS or by pushing the NDTA development even further and introducing the High Definition Fiber Optic Sensing (HD-FOS) tools.

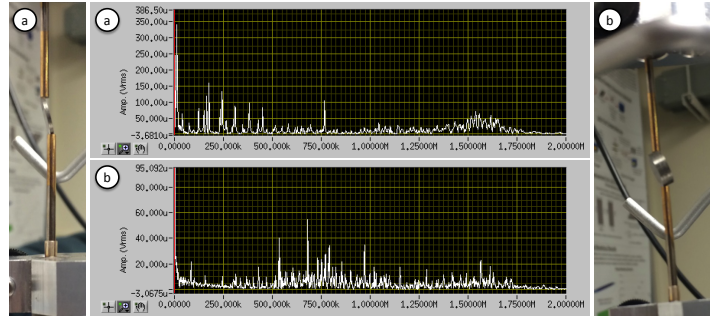


Fig. 5. Preliminary RUS testing results for
(a) 1mm thick Niobium (Nb) sample and (b) 3mm thick Niobium (Nb) sample

First material samples were cut in the lab, made of the same batch of Niobium (Nb) with the one utilized for the manufacturing of the ESS spoke cryomodule cavities. The preliminary RUS testing results are presented in Fig. 5, with the corresponding Fourier transformation induced by a broadband excitation on 3mm and 1mm thick samples, respectively. For this draft test configuration, free oscillation is allowed on the samples with only two (2) points of contact with the relevant ultrasound pinducers.

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